Cross-scale Information and Decision-Making Systems for Common Pool Resources: Water Management of the High Plains Aquifer in the U.S. Great Plains

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David W. Cash

Belfer Center for Science and International Affairs
John F. Kennedy School of Government
Harvard University
Cambridge, MA 02138 USA
Telephone: +1 (617) 496-9330
Fax: +1 (617) 496-0606
Email*: david_cash@harvard.edu*

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David W. Cash

1. INTRODUCTION

Between 1940 and 1995, the High Plains[1] Aquifer, a major source of irrigation water underlying eight U.S. states in the semi-arid Great Plains, declined in some areas by as much as 50%. Depletion of the High Plains aquifer exemplifies a specific class of common pool resource (CPR) problems which are characterized by cross-scale interactions - *those in which events or phenomena at one level influence phenomena at other levels*. These challenges of such problems are becoming more apparent with the increasing political and scientific focus on international and global commons. Commons problems of this nature have historically posed unique problems and pitfalls for management, and this research identifies three such challenges: 1) matching scales of biogeophysical systems with scales of management systems, 2) avoiding scale discordance (matching the scale of the assessment with the scale of management), and 3) accounting for cross-scale dynamics. Specific examples of pitfalls arising from such challenges include: appropriations, enforcement and conflict resolution rules imposed by higher-level jurisdictions that are incompatible with local conditions; scientific and technical information produced at one level that is not relevant, usable or credible at other levels; and monitoring changes in large-scale commons that are influenced by local activities.

Despite the existence of these pitfalls, relatively little research has focused on how the multi-level nature of commons problems can contribute to management challenges, and what mechanisms exist to avoid such pitfalls. In fact, research that even addresses the multi-level nature of commons problems often casts the problem in terms of a simple dichotomous decision choice between centralized (higher-level) control and local control (Adams 1990; Bruggink 1992; Somma 1994; Avalos and DeYoung 1995). Another vein of research in the CPR literature, however, has provided more nuanced interpretations, and have better problematized scale (Ostrom 1990; Blomquist 1992; Ostrom 1998). This paper extends this latter research, looking beyond what appear to be false dichotomies, and mapping the institutional mechanisms which support multi-level commons management.

As such, this research investigates what kinds of challenges exist and what responses to a cross-scale problem - in this case, irrigation-induced depletion of the High Plains Aquifer - result in effective and sustainable management strategies, focusing on how information and decision-making systems can be structured to support such management. In this effort, groundwater management regimes are compared in Kansas, Nebraska, and Texas. This study suggests that effective cross-scale management of a CPR is associated with:

[1] The High Plains Aquifer is more popularly referred to as the Ogallala Aquifer, the largest of the aquifers that make up the High Plains Aquifer system.

1) the use of **boundary organizations** to coordinate across levels. Boundary organizations are institutions which mediate between decision-makers and scientists across different levels and are characterized by systems of accountability on both sides of the boundary, multi-directional communication (e.g., users' needs, producers products), multi-level participation, information brokering/translation.
2) capitalize on **scale-dependent comparative advantages** including technical capacity (e.g., modeling, data collection, etc.), functional specialization (local tailoring of regulations, option creation, monitoring, enforcement, funding, education, etc.), and enabling rule-making which decreases constraints and provides opportunities (economic, institutional, boundary crossing/translation, educational, etc.)
3) establish an **adaptive process** which is long term, iterative, flexible (designed to accommodate and address both endogenous and exogenous technical, political and environmental changes), and provide technical means of addressing scale mismatches through policy and assessment experimentation.

While this case focuses on a CPR in the U.S., the implications of this research for international and global commons management are addressed.

2. THE CASE AND METHODS

2.1 Water Management of the High Plains Aquifer

The primary focus of this paper is on management of the High Plains Aquifer. Derived from stream-borne sediments which originated in the Rocky Mountains, the High Plains Aquifer is a subsurface geologic formation deposited 3.8 million years ago. The aquifer underlies an area of 174,000 square miles (for comparison, the area of New England is 67,000 square miles) (McGuire and Sharpe 1997). See Figure 1. Consisting of a layer of unconsolidated clay, silt, gravel, and sand, the formation is saturated with water and can be several hundred feet thick.

{Insert Figure 1 about here}

A wide range of factors influence the rate of recharge, or replenishment, of the aquifer including precipitation, soil type, vegetation, permeability of the substrate, irrigation return-flow, and seepage from streams, canals, lakes, and reservoirs. Within the aquifer, recharge rates range from .25 inches per year to 6 inches per year (McGuire and Sharpe 1997). This relatively slow recharge rate combined with pumping rates of as much as 30 inches per year, has resulted in utilization of High Plains aquifer water being referred to as mining. In many places in the region, the resource is essentially non-renewable (Green 1992).

The geologic nature of the aquifer results in especially good quality water, as the substrate acts as a purifying filter (Buchanan and Buddemeir 1993). The high quality of ground water, the climatic variability and semi-arid nature of the area led to pumping for irrigation in the late 1880's as early farmers attempted to secure a predictable source of water. Despite some advances in pumping and energy technology in the 1890's and early 1900's, the great increase in development of the aquifer did not begin until the 1930's when the dust-bowl drought and New Deal-era government programs provided incentives for farmers to exploit the groundwater (Green 1992). Further technological advances in drilling, pumping, and delivery, and the advent of inexpensive energy, favorable financing, government subsidies and crop prices all contributed to steady increases in irrigated acreage from WWII to the present (see Figure 2).

{Insert Figure 2 about here.}

Currently, approximately 95% of water withdrawn from the aquifer is used for agricultural purposes (McGuire and Sharpe 1997). Irrigated cropland accounts for 37% of the harvested cropland in the High Plains region, and for specific crops such as corn, 50% of the harvested cropland is attributed to irrigated acres (Kromm and White 1992). From a national perspective, the region produces significant shares of the U.S. output of corn, wheat, sorghum, cotton, and cattle (fed on irrigated feed). Clearly, "[i]rrigated agriculture sustains the High Plains and is central to an integrated agribusiness economy…." (Kromm and White 1992).

With relatively low natural recharge rates and the dramatic increase in the use of groundwater throughout the region, declining water levels were noticed in parts of the region as early as the 1940's and 1950's (McGuire and Sharpe 1997). By the 1970's, farmers and officials at all levels of government were expressing a need to more closely examine the issue of aquifer depletion. In the mid-1970's the U.S. Congress authorized two assessments. The first was a national effort, the Regional Aquifer-System Analysis, undertaken by the U.S. Geologic Survey (USGS), which examined the hydrogeology of all the major aquifers in the U.S. The second assessment process brought together federal, state, local government agencies with private consultants within the High Plains region to analyze the potential economic and social impacts of aquifer depletion and management options (High Plains Associates 1982; Weeks, Gutentag et al. 1988; Kromm and White 1992). This assessment was performed in parallel with hydrogeological studies conducted by the USGS. Motivation for these studies at the national level centered on national food security issues. The local and state concerns focused on potential negative local and state economic and demographic impacts of partial or total depletion of the aquifer. At the time, increased pumping costs, due to both the increasing depth to water and the energy price shocks of the mid- and late-1970's, as well as the potential social disruption due to the abandonment of irrigated farming in the region placed concern for the aquifer high on the public's agenda.

One of the central issues that also focused state and local attention during this time was the common pool resource attributes of the aquifer. While pumping water in Nebraska will have no discernable impact on water levels in Texas, at local levels (farms, counties, and immediately across jurisdictional lines), exploitation of the resource at one point decreases water availability at other points. In addition, current research, management and legal concerns are focusing on the relationship between ground and surface water, particularly on how depletion of the aquifer affects surface water levels and vice versa.By the mid-1980's, both the USGS, states and multi-county water management districts within the region had undertaken individual and collaborative ongoing monitoring, analysis, and modeling efforts to assist in the management of the resource, often involving the CSREEES (McGuire and Sharpe 1997).

Given the increasing concern about the condition of the aquifer, states in the region have implemented a wide range of legislative and institutional responses. In all three states, for example, legislation has provided for the creation of local (single or multi-county) groundwater management districts which have varying degrees of autonomy and authority. The largest variance between the three states, however, is in the degree to which decision systems are coordinated across scales (See Section 4.2.3. , below for discussion).

Given the national, state, and local concerns and the common pool characteristics of the resource, it has been increasingly identified as a multi-level problem, requiring attention at many scales of organization.

2.2 Methods: Research sites

As discussed above, the geographic focus of this study is the High Plains region in the U.S. Great Plains. One primary reason for studying this region is that it allows for a comparative analysis within the region. For example, within the High Plains region there is variance in both natural conditions (e.g., precipitation, temperature, soil type, storm frequency, aquifer saturated thickness and recharge rates) and, more important, variance in management institutions and their relation with other state and local entities. Within the region, however, there is relatively little variance in overall socio-economic, industrial, and cultural makeup.

Nine counties in Kansas, Nebraska, and Texas were chosen as field sites for data collection (see Figure 3). These three states were chosen because: 1) they overly 75% of the aquifer (McGuire and Sharpe 1997); 2) they account for 89% of the irrigated acreage overlying the aquifer (Kromm and White 1992); 3) within each of the three states, the heterogeneity of the aquifer is represented, so variance of the natural resource itself can be controlled for; 4) agricultural production and irrigation development have taken similar paths in the three states, and thus a range of economic factors can be controlled for; and 5) there is useful institutional variance in water resource information and decision-making - for example, all three states have evolved three different ways of managing the aquifer at the state and local levels; and all three states have different relationships with federal agencies such as the USDA and USGS. The counties were chosen for this phase of the research because the level of risk of depletion, measured by saturated thickness, depth to thickness and historical rates of decline, faced by each is relatively similar, and thus controlled for. Thus, for this phase of the research, variables such as the characteristics of the aquifer, risk of water depletion, and general economic characteristics are held relatively constant, while specific institutional and management variables vary.

{Insert Figure 3 about here.}

2.3 Methods: Data collection

Two sources of evidence have been used in this investigation. The primary source of evidence derives from structured interviews completed in the states and through telephone interviews in Washington D.C. using a consistent interview protocol (Moser and Cash 1998). In particular, the interviews established what types of scientific information decision-makers need, which sources they turn to, why certain sources are preferred to others, what were the characteristics of the decision-making process, and what were important links in information flow. Over 80 interviewees in the three states and at the federal level were selected through an iterative process from a number of sources: from the pertinent literature; through U.S.-wide and state-specific searches for non-governmental, governmental, academic and non-academic organizations involved in agricultural and water resource issues; and finally, once the interviews were underway, through recommendations from interviewees themselves. Interviews were conducted with county and area agricultural research and extension personnel, scientists at land-grant colleges, USDA scientists, Natural Resource Conservation Service educators, private industry managers, state and local planners, representatives of non-governmental organizations, and elected officials and the staff of local water management boards.

The second source of data complements the first and is comprised a survey distributed to the 220 county agricultural educators in Kansas, Nebraska, and northern Texas. The survey probed similar questions as the interview but was more structured, and focused on the county educators' involvement in collaborative efforts and multi-level linkages. The response rate was 74%.

3. RESULTS: CHALLENGES FOR MULTI-LEVEL COMMONS MANAGEMENT

I begin this discussion by clarifying the fundamental concepts I use. For the purposes of this paper, "scale" refers to any specific geographically or temporally bounded level at which a particular phenomenon is recognizable. "Scale" can also – and sometimes simultaneously – imply a level of organization or a functional unit (Ahl and Allen 1996). It is recognized that there is reasonable disagreement on the precise extent or definition of any scale (e.g., where are the boundaries of something "local"?), and that there rarely is perfect congruence of, for example, a spatial and a functional unit identified at the same scale (Clark 1987; Sayer 1991). This variance is evidence of how scale is socially defined, and particular to certain political, scientific, legal, or cultural lenses. People impose a definition of scale for a particular issue and for particular purposes. As such, scale is a heuristic employed by scientists and managers to organize their understanding of the world and the relationships and interactions therein (e.g., ecologists find it useful to think of trees, forests, and biomes; politicians find it useful to think of cities, counties, states, and nations). In fact, because scale is largely socially constructed, the conceptualization of scale brought to any specific case by particular players is mutable and amenable to adaptation so as to best fit the management of a commons problem. For example, the ongoing regional component of the U.S. National Assessment of Climate Variability and Change has divided the country into 18 regions. The resulting scale at which each region is assessed is critical to the content, tools, and outcomes of the assessment, yet can be changed in future assessments if deemed inappropriate.

Through this research, and research done in collaboration with Susi Moser (Cash and Moser 1998; Moser 1998; Cash and Moser in review), we have identified three problems that are missed by those perspectives because they pay little attention to the multi-scale nature of the problem: scale mismatch between environment and management; scale mismatch between assessment and management; and ignorance of cross-scale dynamics.

The scale lens is proposed as an important additional heuristic to explore and explain some of the challenges that assessors and policy-makers face as they struggle to produce and use credible and salient scientific information.

3.1. Scale mismatch between environment and management – an institutional fit problem

> The boundaries of property and government, like the less sharply etched patterns of markets, rarely follow the outlines of biology and topography. (National Research Council 1996, p. 326)

The problem of matching the scales of the biogeophysical system and the management system is perhaps the most thoroughly studied of the three challenges we highlight. The problem arises when an environmental phenomenon is managed at an institutional scale whose authoritative reach does not correspond with the geographical scale or particular spatial dynamic of the environmental problem. The challenge for management regimes is to avoid policy pathologies which emerge because environmental and human systems "proceed at [their] own pace and in [their] own space, and that creates extraordinary conflicts when ecosystems, institutions, and societies function on scales that are extremely mismatched" (Holling 1995, p.73). The result is often unsustainable management of the resource (Lee 1993; Folke, Pritchard et al. 1998).

Two illustrative cases demonstrate where underlying institutional structures drive this kind of scale mismatch problem. In the first, an environmental problem is exported beyond certain jurisdictional boundaries to neighboring jurisdictions which have no or little influence over the source of the problem – the case of environmental externalities (Holland, Morton et al. 1996). This is seen, for example, in classic pollution problems such as transboundary transport of acidifying compounds, or water pollution in a watershed that crosses political boundaries.

The other case includes the classic "tragedy of the commons" problem (Hardin 1968), frequently discussed in the common pool resources literature. It is argued, for example, that the proper management of common pool environmental resources depends on centralized (higher-scale) control and management and/or on coordinated collective action and the establishment of institutionalized norms and rules for behavior (Hardin 1982; Ostrom 1990; Bromley 1992). Examples include the management of underground aquifers, ocean fisheries, or sediment budgets in littoral systems. In recent years, the atmosphere has come to be framed as a global commons as well.

With increased understanding of transboundary and CPR management challenges, and often in response to spectacular management failures, both governmental and non-governmental activities have been undertaken to address these scale mismatch problems. From the late 1970's through the passage of the U.S. Clean Air Act Amendments in 1990, for example, tropospheric ozone pollution moved from a local issue to one which involved regional consortia and collaborative efforts of multiple state and local actors under federal guidance (Portney 1990; Keating and Farrell 1999). Trends in water resource management also exhibit this shift. Increasingly, water issues are dealt with on the scale of watersheds, with collaboration across political jurisdictions (Francis and Reiger 1995; Rabe and Zimmerman 1995). Despite these changes, however, scale mismatch continues to be an endemic problem.

3.2. Scale mismatch between assessment and management – a scale discordance problem

> As climate change matures both as a scientific and as a political issue, and as policy-makers increasingly want assessment results to enter into policy- and decision-making, the problem of scale discordance is becoming ever more prominent. Resource planners and managers interested in utilizing climate model output as part of their operational activities immediately confront the dilemma of scale discordance. Their functional responsibilities cover relatively small geographical areas and necessarily require data of relatively high spatial resolution. Climate models cover a large geographical, i.e., global, domain and produce data at comparatively low spatial resolution (Lins, Wolock et al. 1997, p. 63).

Essentially, the discordance is between the scale of scientific analysis and assessment and the scale for which scientific information is needed to usefully inform management. This challenge is illustrated in Figure 4, in which the risks associated with the change in a global commons, such as the climate, are plotted as a function of scale. At large scales, where assessments might aggregate social welfare, the *overall* impacts (costs) of climate change are relatively small. Assessments which focus on more local scales, however, reveal an underlying pattern of widely ranging costs and benefits, with some large winners and some large losers (Environment Canada 1997). In this case, assessments which are undertaken at large scales of analysis might have little to offer to managers at smaller scales, who might be primarily concerned with the distributional effects of changes in the CPR. These managers need analyses with greater resolution, one that can disaggregate costs and benefits. Inversely, assessments which focus solely on local-scale impacts might not be useful to policy-makers at higher scales who might be ultimately interested in aggregate social welfare. This discordance illustrates why decision-makers and resource managers increasingly demand that assessments be scaled up or scaled down, whichever is appropriate (Wessman 1992; Lins, Wolock et al. 1997; Schubert 1997; Harvey 2000).

{Place Figure 4 about here}

The need to scale up and down between the global and the local in order to address data resolution needs is evident in, but not limited to, three related trends in environment and natural resource science and policy, as illustrated by the case of climate change. The first is seen in the efforts to identify patterns of contributions to greenhouse *forcing* at various, and increasingly smaller, scales. The goal of this effort is to better characterize and understand causal relationships between local human behavior, greenhouse gas emissions, and global climate change, and to establish a reliable accounting system for emission reductions which is key to more successful international climate negotiations (Intergovernmental Panel on Climate Change 1996; Wilbanks and Kates 1999; Harvey 2000). The second trend is driven by both climate scientists and national and subnational policy-makers who wish to better identify, understand, and predict smaller-scale environmental and socio-economic *impacts* of climate change (MINK Project 1991;

Office of Technology Assessment 1993; Environment Canada 1997; Lins, Wolock et al. 1997; Intergovernmental Panel on Climate Change 1998). Third, interests within the science and policy communities have recently shifted to focus on *adaptation* responses to global climate change, and the ultimately local nature of such responses (Environment Canada 1997; U.S. Global Change Research Program 1999).

Despite this increasing demand for down-scaled models of climate change and rapid improvements in computer technology and scientific understanding, assessors have not been able to keep up with the growing demand for more useful, higher-resolution models and data (Kattenberg, Giorgi et al. 1996; Easterling 1997; Houghton, Meira Filho et al. 1997; Shackley, Young et al. 1998). Thus, the problem of scale discordance persists and has become more pressing in light of the political interest of national and sub-national governments and of the private sector to respond to climate change.

At least three problems ensue from persistent scale discordance. The first is that explanations and predictions of climate change lack credibility for regional and local decision-makers. Assessors are unable to predict impacts at local scales, and can therefore say nothing definitive and credible about local impacts. This lack of local specificity often leads to a complementary lack of credibility about what assessors say about climate change in general. This skepticism is compounded by the fact that assessment efforts which only produce outputs of large-scale impacts rarely provide local decision-makers with the tools to use that kind of output. The second problem is the dearth of *relevant* outputs that are useful to and useable by regional and local decision-makers. Without local specificity and detail, the issue at hand lacks salience and decision-makers are unable to either understand the potential impacts of climate change, or formulate scale-appropriate adaptive responses (Easterling 1997; Lins, Wolock et al. 1997). Finally, decision-makers always face situations in which decisions are made under conditions of uncertainty. In the case of climate change, science may not be able supply the desired resolution of climate information in the near future. In the meantime, decision-makers must find the types of policies and management strategies for which scale-specific, adequate information already exists. This may imply, for example, early institution of enabling policies or insurance schemes at higher scales while postponing specific adaptation actions at the local scale.

3.3. Accounting for linkages between different scales – a cross-scale dynamics problem

Though the multi-scale nature of environmental problems has in some cases been acknowledged, and efforts have been made to match scales of problem and management, science and policy-making often pay most attention to just one of the relevant scales of a problem, thereby missing important *cross*-scale interactions – *those in which events or phenomena at one scale influence phenomena at other scales* (Holling 1978; Holling 1986; O'Neill 1988; Gunderson, Holling et al. 1995; Holling 1995; Gibson, Ostrom et al. 1997; Peterson and Parker 1998). "Where global change is concerned, it can be argued that a focus on a single scale tends to emphasize processes operating at that scale, information collected at that scale, and parties influential at that scale – raising the possibility of misunderstanding cause and effect by missing the relevance of processes that operate at a different scale" (Wilbanks and Kates 1999, p.8).

This challenge is illustrated, again, in Figure 4. If global change is assessed at only one scale, and thus only one characterization of the distribution of costs and benefits is analyzed, a more complete picture of the underlying structure of impacts is foregone. Thus, little is learned about how the distribution of costs and benefits at one scale influences and is linked to available political response strategies at other scales.

Hierarchy theory offers one approach to explore these linkages in biogeophysical and social systems. It facilitates the ordered examination of complex systems by disaggregating them into *interacting* processes and structures at different scales (Simon 1962; Allen and Starr 1982; Salthe 1985; O'Neill 1988). Its central idea is that a phenomenon at a chosen scale of interest is the synergistic result of both the smaller/faster dynamics of system components at the next lower scale and the constraints imposed by the generally slower/larger system dynamics at the next higher scale. The only way that the system can be meaningfully understood at any one scale is to simultaneously capture the driving and constraining forces at both lower and higher scales (Pattee 1973; Holling 1978; Holling 1986; O'Neill 1988; Holling 1995). For example, in order to understand regional precipitation patterns, an important variable in underground water management, it is necessary to understand large-scale climatic forces as well as local-scale topographic characteristics.

While issues of cross-scale dynamics in social systems have not been as thoroughly examined as in natural systems (Gibson, Ostrom et al. 1997), analyses of federalist systems of governance by political scientists, economists, legal scholars, and political economists have illuminated the links connecting different scales in hierarchical political or decision-making systems. The federalist literature examines, for example, how governmental (i.e., legislative, regulatory, monitoring, or information-producing) actions that occur at one scale influence the suite of actions available to, or mandated by, decision-makers at other scales (Percival 1995; Holland, Morton et al. 1996). As in the case of complex natural systems, research in federalism maintains that in order to understand political behavior at any specific scale, it is important to understand the various political, economic, and social drivers and constraints at neighboring scales. Thus, for example, to understand water policy and management on the scale of a state, it is critical to understand the context of federal regulations and water-related assessment efforts, as well as local water use practices and regulatory regimes. Examining such cross-scale dynamics frequently entails the difficult challenge of integrating knowledge produced at these respective scales which might be characterized by quite disparate methodologies and disciplinary approaches.

Finally, there is little understanding of what the cross-scale interactions in both human and environmental systems mean for the movement of information across, and the differential needs for knowledge at, different scales. The traditional approach to incorporating scientific information into the policy process has been to produce scientific assessment reports and then to funnel them to policy-makers – an approach we caricaturize as the pipeline model of information dissemination. This model is particularly common in the top-down approach to the provision of policy-relevant scientific information about multi-scale problems in which it is presumed that science produced at a higher scale (e.g., a national report) will be assimilated and used "as is" at lower scales (e.g., by states or municipalities) (Lindblom 1990; Kingdon 1995). One fundamental problem with this approach is that it ignores the *interactions* between actors located at different scales. It is critical for the design of assessment and outreach processes, for example, to understand how coastal scientists conducting global analyses of sea-level rise interact and communicate with scientists studying local impacts of that process, and what kind of credibility each has with the other; or how national coastal assessors interact with coastal zone managers and public and private decision-makers at the state or local scale (e.g., how credible they are or how research and assessment agendas are set); or in what format, frequency, and style information is needed and communicated to be most useful to decision-makers located at different scales.

4. RESULTS: TENTATIVE DESIGN GUIDELINES FOR MANAGEMENT OF MULTI-LEVEL COMMONS PROBLEMS

The fundamental challenges outlined above are faced by the producers and users of information when addressing multi-scale commons problems. Below I build on both the theoretical advances made regarding these challenges and on my own (Cash 1998) and others' empirical research to propose three broad design guidelines for addressing cross-scale commons problems. In essence, I provide a framework of hypothesized attributes of effectively integrated information and decision systems.

4.1. Utilize boundary organizations

In thinking systematically about the interface between science and policy in the addressing commons issues, I draw on the science studies literature which conceptualizes this interface, not as a sharp line or demarcation, but as a fuzzy, dynamically shifting and jointly created and maintained *boundary* (Jasanoff 1987; Jasanoff 1990; Gieryn 1995). This boundary is negotiated, contested, and maintained by both scientists and decision-makers as they struggle to resolve a fundamental tension that emerges when science is brought into the policy arena: maintaining scientific credibility while assuring political saliency (Jasanoff 1987; Jasanoff 1990). *Boundary organizations,* institutions that straddle and mediate the divide between science and policy, are established to help in this task (Guston 1999).

The concept of boundary organizations is used in the science studies literature only in the context of the science/policy interaction, but it is equally useful for describing the boundaries between different scales or functional levels (Cash submitted manuscript). In this application, boundary organizations serve to mediate between scientists and decision-makers on the one hand, and between these actors at different scales on the other. Thus, the conceptual model of boundary organizations provides a powerful alternative model to the pipeline model of transfer and use of scientific information. In the boundary organization model, rather than being passive recipients of information, decision-makers are involved in the creation and maintenance of the relationship with scientists, the science-policy boundary, and the scientific and technical outputs. As opposed to the unidirectional flow of information in the pipeline model, boundary organizations facilitate the multi-directional flow of information (i.e., needs, output format, results, etc.) between science and decision-making and across scale.

From a normative perspective, boundary organizations may be considered essential elements of a cross-scale assessment design in which either existing or new boundary organizations are engaged. They serve to resolve the tension between policy and science described above, and they facilitate the convergence of interests, ideas, disciplinary languages and perspectives at different scales. Boundary organizations can accomplish this, for example, by producing outputs (referred to as *boundary objects* in the social studies of science literature) that are valued on both sides of the boundary and provide a site for cooperation, debate, evaluation, review, and accountability (Star and Griesemer 1989; Guston 1999). Examples of such outputs include reports (e.g., Intergovernmental Panel on Climate Change reports), models (e.g., the Regional Air Pollution Information and Simulation, or RAINS, model, used in the negotiation of the Convention on Long-Range Transboundary Air Pollution in Europe or various hydrologic models used the High Plains region), forecasts (e.g., ENSO predictions), or newsletters (e.g., the *Pacific ENSO Newsletter* produced by the Pacific ENSO Application Center). Boundary organizations have been enrolled to mediate across boundaries for a wide range of environmental and natural resource issues.[2]

As intermediary institutions, boundary organizations can provide five important functions (Guston 1999; Cash submitted manuscript) illustrated by using the Cooperative State Research, Education, and Extension Service of the U.S. Department of Agriculture (CSREES) as an example (Youmans, Weber et al. 1988; Rasmussen 1989; National Research Council 1996; Cash submitted manuscript).

1) *Information brokerage – Mediating information flow across levels*]: One fundamental component of the CSREES is the county extension office. Extension agents[3] within these offices act as information translators, acquiring both basic and applied research from state agricultural colleges[4], CSREES regional research and experiment stations, USDA research facilities, and private industry, and packaging it in ways that are usable by farmers or local elected officials. Thus, one of the primary functions of CSREES has been to facilitate communication between the local, state, and federal levels. This is seen, below for example, in the discussion of county educators' role in linking farmers to state land-grant scientists (the science/decision dimension) in setting research agendas and producing relevant research. It is also seen, however, in the objective of the extension system to link specialists at area experiment stations, research teams at state land-grant colleges, and federal research facilities. Evidence that confirms

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[2] Such boundary organizations include the Pacific ENSO Application Center (between climate scientists studying global phenomena and policy-makers/managers on islands throughout the Pacific region), the Cooperative State Research, Education, and Extension Service (CSREES) organized under the U.S. Department of Agriculture (USDA) (between federal, state, and locally situated scientists, and between scientists and farmers), the IPCC (between national diplomatic delegations and climate scientists studying global and regional scale climate); the Consultative Group of International Agricultural Research (between international researchers, national researchers, and national and local planners, policy-makers, and farmers); the International Institute for Applied Systems Analysis in its work for the Long-Range Transboundary Air Pollution convention; and the extension service of U.S. Sea Grant colleges (between scientists, coastal management agencies and private resource managers.)

[3] Individual states have wide latitude in how the extension system is structured from the state to the local level. County extension agents, for example, are also called extension educators in some states, but the difference in function is minimal. The degree to which these agents (or educators) are affiliated with the agricultural college, are included as faculty, or have tenure-track positions, also varies from state to state.

[4] In the U.S., agricultural colleges are more formerly known as "Land-Grant" colleges or universities, names derived from legislation in the 1860's which granted federal land to the states for the purpose of establishing agricultural colleges.

that this occurs draws on the results from the survey of county extension educators. If CSREES' objectives are being met, for example, one would expect to see communication between county educators and researchers at multiple levels. This is displayed in Figure 5, in which the frequency of communication between county extension educators and others at different levels is plotted. While county educators do not talk to *all* players at multiple layers (note the low frequency of communication with the Washington office of the USDA or the Area Water Management District), they do communicate frequently with local farmers, scientists representing area (multi-county) research stations, and scientists at the state land-grant colleges. Not surprisingly, the majority of communication happens within the extension system or with its clients (farmers).

{Insert Figure 5 about here.)

2) *Communication of salient research needs to scientists*: Each county has an elected or voluntary committee of citizens who regularly suggest research and program concerns to county agents who then communicate these items to state and USDA researchers. These researchers in turn set their research agendas based partly on this local input. In this way, problems like scale discordance are minimized as higher scale researchers can incorporate local concerns and data into larger scale assessment efforts. Given their role as communicators across scales, county agents are accountable to both clients at the local level, and scientists at the state and federal levels.

3) *Insulation from pressures emanating from across the boundary*: Scientists within the CSREES generally have faculty appointments at state agricultural colleges. As faculty members, they maintain academic standards and autonomy and are subject to similar norms (peer review, tenure, etc.) which maintain their credibility in the scientific arena and also insulate them from political intrusion.

4) *Neutral fora for discussion*: The research and extension system provides a wide range of fora, e.g., seminars, conferences, and informal publications, in which ideas, research findings, and implications for application can be shared and vigorously debated.

5) *Long-term trust building*: While the CSREES has evolved over its 125 year existence, the multiple institutionalized avenues of communication and feedback, and the multiple and shared sources of funding (from county, state, and federal levels) has produced a system which has engendered mutual respect and trust between farmers, county agents, researchers, and administrators across all scales (Cash 1998). Well established boundary organizations like the CSREES with their trusted, well connected experts could be instrumental building blocks of an assessment process which aims to effectively and usefully mediate between the needs of information users and decision-makers and the community of scientific experts.

4.2. Utilize scale-dependent comparative advantages

A second critical design choice addresses the need for greater institutionalized cross-scale coordination to further address scale discordance, mismatch and cross-scale dynamics. While calls to do so are not novel, *how* to achieve such coordination is a more challenging and engaging question. One specific way to do so is to harness scale-dependent comparative advantages. Such comparative advantages can be thought of as unique knowledge, technical capacity, or functional specialization characteristic of a specific scale.

With increasing efforts to understand local implications of large-scale phenomena and to explore options for adaptation to environmental change, it has become increasingly important that unique and local knowledge be brought to bear on assessment and management (Dickson 1999; Wilbanks and Kates 1999). This is evident, for example, in the local and regional input solicited in the current U.S. National Assessment of Climate Variability and Change (U.S. Global Change Research Program 1999).

4.2.1. Technical Capacity

Scale-dependent technical capacity refers to the differing abilities of organizations at different levels to undertake various scientific and technical functions such as data collection, monitoring, modeling exercises, and analysis (Blomquist 1992; Lins, Wolock et al. 1997).

For example, for water management in the U.S. Great Plains, a federal agency such as the U.S. Geologic Survey is particularly well suited to conduct large-scale (multi-state) hydrologic modeling of surface and groundwater interactions – it's "jurisdiction" crosses state boundaries so it can cover the full extent of large aquifers or rivers which cross state lines. Furthermore, as a large federal agency, it has the financial, computing, and human resources to undertake complex modeling exercises. Any one state does not have these capacities, but might have the capacity to store and systematize water data within its boundaries. Finally, local water districts have the unique ability to engage individual landowners in collecting data on numerous characteristics of the resource at local well monitoring sites, thus contributing to a state-wide database. Each level is dependent on the unique capabilities of data collection, analysis, and interpretation at other levels in order to construct a model that both accurately captures large-scale system dynamics, and can also be "ground-truthed", while being relevant and credible for different purposes at different levels.

Throughout the High Plains there is wide variance in the exhibition of this cross-scale coordination. County agents in Kansas and Nebraska have successfully solidified long-term collaborative efforts between farmers, area specialists, managers in the local water management district, scientists at the land-grant college and state geologic service, and scientists at USGS. Through these efforts, models have been produced which have been instrumental in providing information to local management districts, local farmers, and state water agencies (e.g., depletion rates, predicted changes in the aquifer and farm income resulting from different management regimes, etc.). This information has been critical for decisions about regulating pumping quantities, experimenting with water transfers and pooling, and determining critical zones that require more stringent regulation.

By contrast, several county extension offices in Texas have not created such a network that links local constituencies to state or federal scientific agencies (e.g., the Texas Water Development Board or USGS) in the context of water management. The boundary has not been successfully bridged, and modeling efforts of the kind described above, which take advantage of different capabilities at different levels, do not exist in these areas. In one area in northern Texas which, like parts of Kansas and Nebraska is part of a multi-county water management district, the managers of a local water management district want to begin imposing pumping regulations on its' constituents but do not have the scientific assessment in place to help guide them in defining specific limits. They have enough information to know that there is a depletion problem, but not enough to effectively address it. It is only recently that some county extension offices are trying to create the kind of network that in parts of Kansas and Nebraska have resulted in coordinated assessment efforts characterized by capitalizing on strengths of different entities at different levels. Thus, where the boundary organization exists and performs the function of coordination across levels, the effective integration of scientific expertise and knowledge at different levels helps produce useful and relevant scientific products that guide management decisions. Those areas without organizations which perform this function are not as successful in this regard.

4.2.2. Functional specialization

Decision and policy functions also vary with scale and may best be harnessed by having different functions performed at different levels. For example, the recent move toward devolution of some environmental regulation and resource management authority to state and local levels reflects both a desire to take greater local control of resource management, and to better tailor policy choices to local conditions (Donahue 1997). Activities such as research funding, enforcement, education, monitoring, and evaluation may be undertaken better at different levels, and hence require that authority, responsibility, and resources be allocated accordingly. Thus the design choice is not simply one between a centralized or decentralized (top-down vs. bottom-up) assessment and management system, but rather one that integrates the unique capacities and complementarities at the "top", the "bottom", and the "middle."

For example, there is a relatively high degree of coordination in Nebraska where the state legislature, state courts, state agencies and the local Natural Resource District (the multi-county district with authority for water management) orchestrate their decision-making and have institutionalized ways to avoid making decisions at one level that constrain decision-making at other levels. While Kansas has similarly institutionalized cross-scale coordination of decision-making, there are still discordant aspects of the system. For example, there has been poor coordination around the role of enforcement, and neither state nor local institutions have undertaken enforcement activities. In Texas, *lack* of decision-making coordination has been institutionalized through water rights laws which constrain local management regulatory efforts. This has not constrained, however, other management efforts, such as education or cost-share incentive programs.

4.2.3. Enabling policies

Allocating assessment and management responsibilities to various scales is effective when complemented by "enabling" policies which are constructed at a higher level of governance (e.g., the international or national level). They provide opportunities for, or at least remove constraints on, local decision-making (Ostrom 1990; Blomquist 1992; Ostrom, Gardner et al. 1994). As described above, the design and implementation of these kinds of polices requires coordination across scales.

An example of this in the High Plains region is state legislation in Nebraska which allows Natural Resource Districts relatively wide latitude in the kind of regulatory and management actions that can be implemented. Given this latitude, several districts have begun experimenting with water "pooling" and "banking" (provisions which allow trading water rights across space and time). Water managers in Kansas are also interested in experimenting with such management tools, but currently state legislation has limited the local management districts.   For many districts this is seen as a lost opportunity to make gains from trade while making water allocation and use more efficient.

Profiting from such scale-dependent comparative advantages requires not only identifying particular advantages, but understanding how they relate to and complement capacities at other scales. This is analogous to long-held notions of utilizing economies of scale, specialization, and division of labor which are well developed in the fields of economics, industrial organization (Chandler 1990) and public management (Sparrow 1994).

Using scale-dependent comparative advantages addresses the challenges outlined earlier in a number of ways. Scale discordance problems are likely to be diminished when parallel and integrated efforts of assessing the problem are undertaken at multiple scales. It also increases the probability that outputs will be better tailored to the needs of decision-makers at different scales as those needs are more directly addressed and matched by technical and institutional strengths elsewhere. Problems matching commons pool resources to management systems are reduced by gaining a more synoptic understanding of the system at all scales and by allowing for multiple ways to view the problem, connecting these problem framings from different scales, and identifying which management schemes best match the environmental system. By utilizing these advantages, assessors and decision-makers will heighten the scientific credibility, reliability, political salience, and practical usefulness of the information for actors at different scales, not in the least because they have been part of and hence familiar with the assessment process.

4.3. Establish adaptive processes

Finally, designing an effective integrated assessment and management system for long-term, multi-scale CPR problems is not likely to be a one-time enterprise. Important choices thus must be made regarding how to create a robust yet flexible process. Over the last two decades, theories and practice of adaptive management have evolved as a potentially powerful framework for the dynamic linkage between science and policy. The central notion of this perspective is that for environmental and natural resource risks characterized by long time horizons and high levels of uncertainty and stochasticity, effective policy should be based on adaptive, iterative, and flexible experimentation. Most characteristically, adaptive assessment and management is a form of explicit learning-oriented policy experimentation to test effective management strategies (Holling 1978; Walters 1986; Lee 1993; Gunderson, Holling et al. 1995; Holling 1995). Such approaches provide fora for multi-stakeholder involvement, and, most important for the purposes of this paper, build on theories that usefully conceptualize how natural and human systems interact across different temporal and spatial scales (Gunderson, Holling et al. 1995; Folke, Pritchard et al. 1998; Peterson 2000). Building flexibility into the linked processes of assessment and management creates the ability to accommodate and address both endogenous and exogenous technical, political and environmental changes.

The description above of water management systems which institutionalize linkages across levels suggests that such systems support adaptability. The modeling exercises that are in place were not one-time ventures, but sustained relationships that, in essence, created a platform from which scientists and decision-makers could assess various issues about the CPR as they arose. For example, modeling efforts which were originally used to address only ground-water quantity issues are now being adapted to deal with ground-water quality issues and ground-water/surface-water interactions, two issues that have recently risen to the top of the agenda of local decision-makers.

In addition to these inferences about adaptability, the survey used in this research was designed to probe the relationship between collaboration across levels as performed by the boundary organization (the county extension office) and the level of adaptive management. County agents were asked questions, for example, about flexibility, ability to use new information to change existing management decisions, and policy experimentation, all components of adaptive management. Answers to these questions were aggregated and categorized into terciles as either indicating low, medium, or high levels of adaptive management. Through a series of independent questions, county agents also reported levels of collaboration with a variety of organizations at local, area, state, and federal levels. These answers were aggregated into either low and high scores of collaboration across levels. Figure 6 displays an analysis of the conditional probability of high levels of adaptive management contingent on the amount of collaboration across levels.

{Place Figure 6 about here}

This analysis shows that those counties which have higher measures of collaboration across levels tend to have a greater degree of adaptive management. While the surveys were not specific enough to discover whether or not the county extension office facilitated the collaboration (that is, other agencies such as the water management district might have taken the lead on facilitating multi-level collaboration), these findings are consistent with those from the interviews which provided similar, if not more nuanced, evidence.

This approach appears particularly promising in the context of multi-scale problems in which perspectives, interests, capacities, and expertise shift as one moves from one scale to another and through time. For example, as describe above, primary concern about aquifer depletion has shifted between local, to state, to federal levels, so to be most effective, assessment and management systems must be flexible enough to adapt to such changing loci of concerns and interests.

Notions of adaptive management suggest that as our understanding of local impacts and adaptation processes grows, assessors and decision-makers, 1) would benefit from incorporating emerging knowledge from different scales, 2) could build on established and trusted communication and interaction channels to reach the most knowledgeable scientists and pertinent decision-makers at different scales, and 3) could receive and incorporate feedback from scientists and decision-makers to respond to the outcomes of management experimentation and thus increase the effectiveness of policies and actions.

Two of the major obstacles to more robust implementation are a lack of long-term institutional stability (resulting from shifting federal and/or state priorities), and organizational cultures characterized by a history of mistrust and conflict which is unable or unwilling to accommodate the risks inherent in experimentation (Lee 1993; National Research Council 1996). Indeed, these obstacles are consistent with empirical analyses of a range of adaptive management efforts which identify at least three critical barriers to the implementation of adaptive management: high costs and risks; threats to existing power structures and interests; and fundamental differences in how environmental resources are valued (Crance and Draper 1996; McLain and Lee 1996; Walters 1997).

5. CONCLUSION

The management of common pool resources are increasingly understood to have implications for assessment and management which span multiple scales, from the local to the global. This multi-scale nature of CPR problems poses fundamental challenges to how both assessors and managers conduct their work, and more important, interact. These challenges include matching scales of biogeophysical systems with scales of management systems, avoiding scale discordance (matching the scale of the assessment with the scale of management), and accounting for cross-scale dynamics.

In this paper I argue that models of CPR management generally do not adequately address the multi-level nature of CPRs. Conceptualizing commons problems through the lens of scale provides an alternative perspective in assessment and management. The model of boundary organizations, for example, suggests a more nuanced relationship between scientists and decision-makers, and proposes mechanisms that account for two-way interactions across levels.

Using these alternative frameworks, I have proposed tentative guidelines for meeting the scale-related challenges when making design choices in establishing assessment and management systems for CPRs: 1) to utilize boundary organizations – institutions which serve to mediate between scientists and decision-makers, and between these actors at different scales; 2) to utilize scale-dependent comparative advantages – coordinating the allocation of resources, technical expertise, and decision-making authority to best capitalize on scale-specific capabilities; and 3) to employ adaptive assessment and management strategies – constructing long-term, iterative, experiment-based processes of integrated assessment and management. While these three strategies do not address all institutional design challenges, they can help address the scale-related challenges outlined in this paper. Empirical research has shown that they help to increase the credibility of participants across scales, and simultaneously better assure the saliency of assessment products for assessment users. Moreover, these three strategies interact synergistically. For example, enduring boundary organizations facilitate adaptive approaches and can help effectively identify and utilize scale-dependent comparative advantages.

The provisional nature of these guidelines and the relative novelty of framing commons problems as cross-scale problems suggests the importance of further research and analysis. With numerous cases now of assessment and management systems which have explicitly addressed cross-scale dynamics, there is a growing empirical base on which to draw that would significantly advance the analysis and theory of cross-scale CPR management, including emerging models of boundary work and boundary organizations. Such research could probe questions such as: How do different institutional forms of boundary organizations influence incentives that face scientists and decision-makers at different levels? What mechanisms can maintain scientific credibility and assure practical relevance? What are the attributes of specific types of CPR problems which make them more or less amenable to cross-scale analysis and management? What types of stakeholder participation (roles, degree of authority, input, etc.) are appropriate in a model of cross-scale assessment and decision-making? How can authority and responsibility for both information production and decision-making be delegated across scales in the context of differing notions of equity, democracy, and expertise?

What we learn from such analytical and theoretical advances could usefully inform the design decisions that many international, national, and sub-national institutions face, now and for future CPR management, and help avoid some of the more damaging pitfalls of ineffective and counter-productive management activities.

FIGURE 1: Extent of High Plains aquifer in the central United States (in dark gray).
(Map derived from U.S. Geologic Survey.)

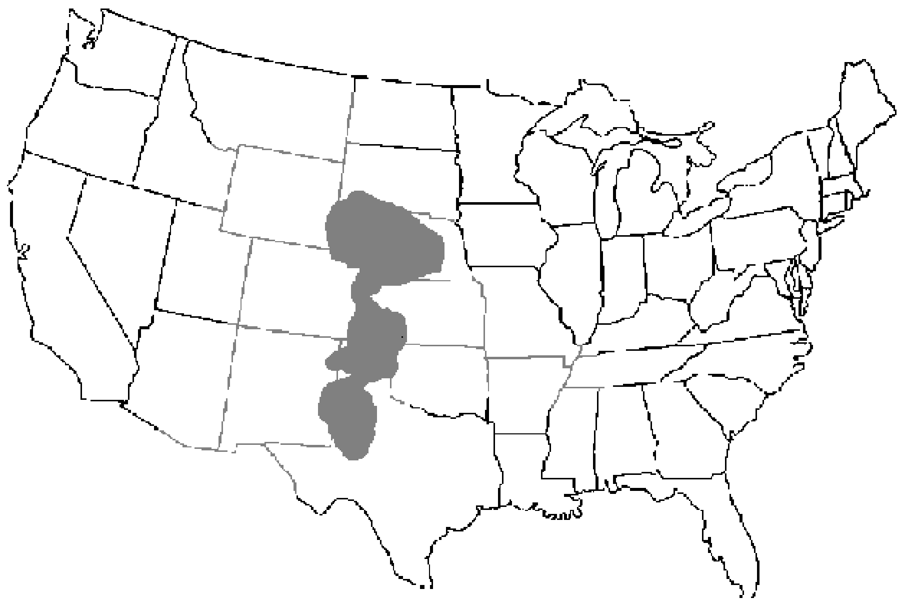


FIGURE 2: Increase in irrigated acres in the High Plains region, 1949-1990. Derived from McGuire and Sharp (1997), U.S. Geologic Survey.

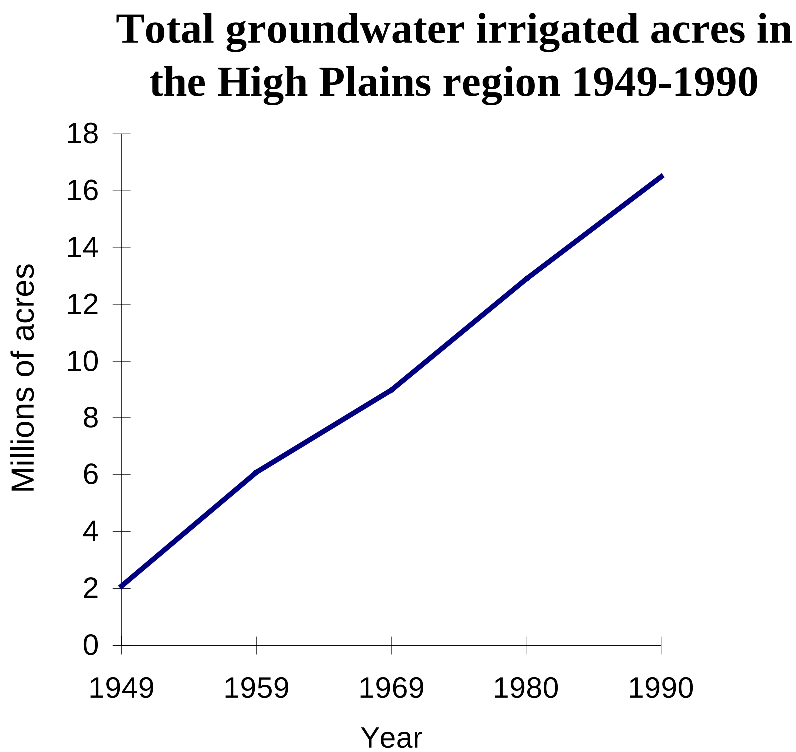


FIGURE 3: Study sites in Nebraska, Kansas, and Texas. (Map derived from U.S. Geologic Survey.)

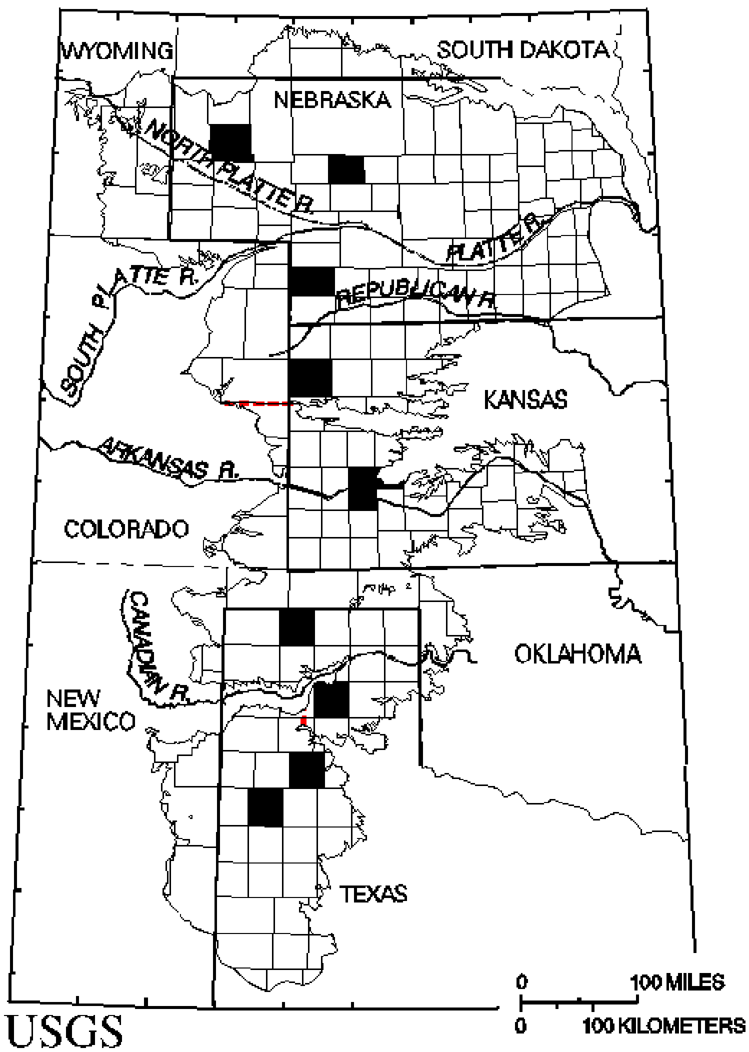


Figure 4: Scale-Dependent Distribution of Impacts

Effects of geographic/economic scale on net gain (benefits minus costs) arising from effects of environmental change on society.

Adapted from *The Canada country study: climate impacts and adaptation, national summary for policy makers* (Environment Canada 1997)

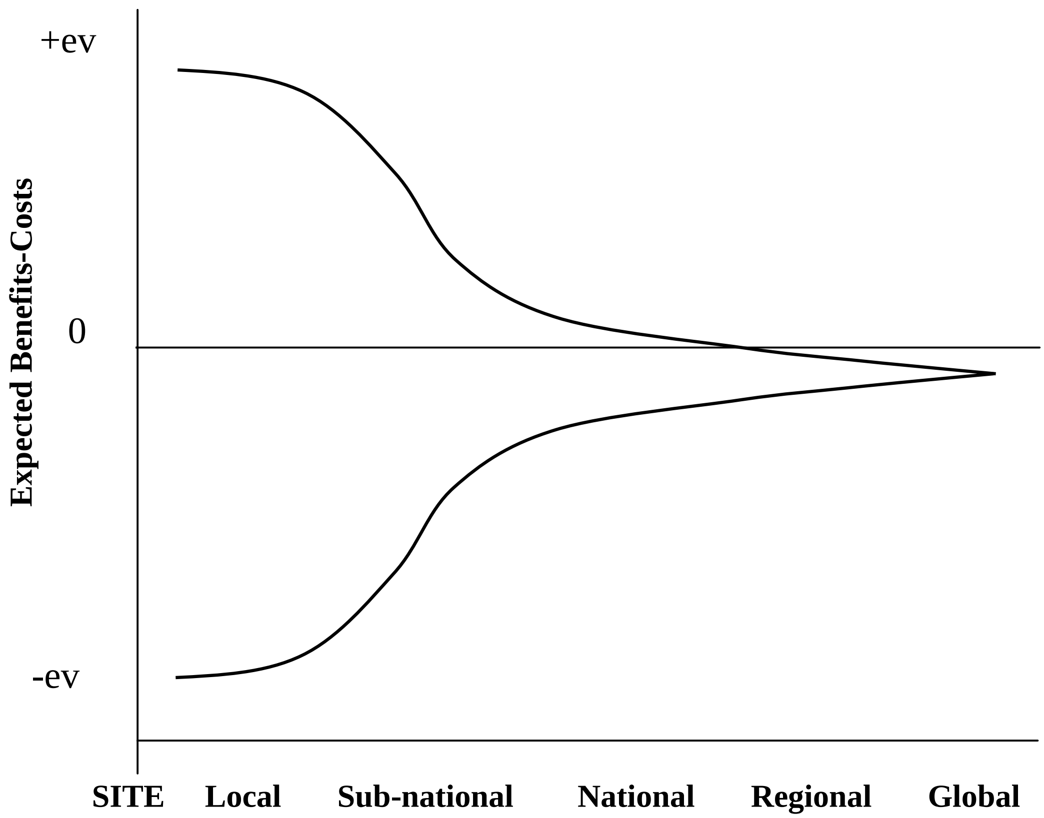


FIGURE 5: Plot of frequency of communication between county educators and other scientists and decision-makers at different levels. County educators communicate frequently from the local to state levels

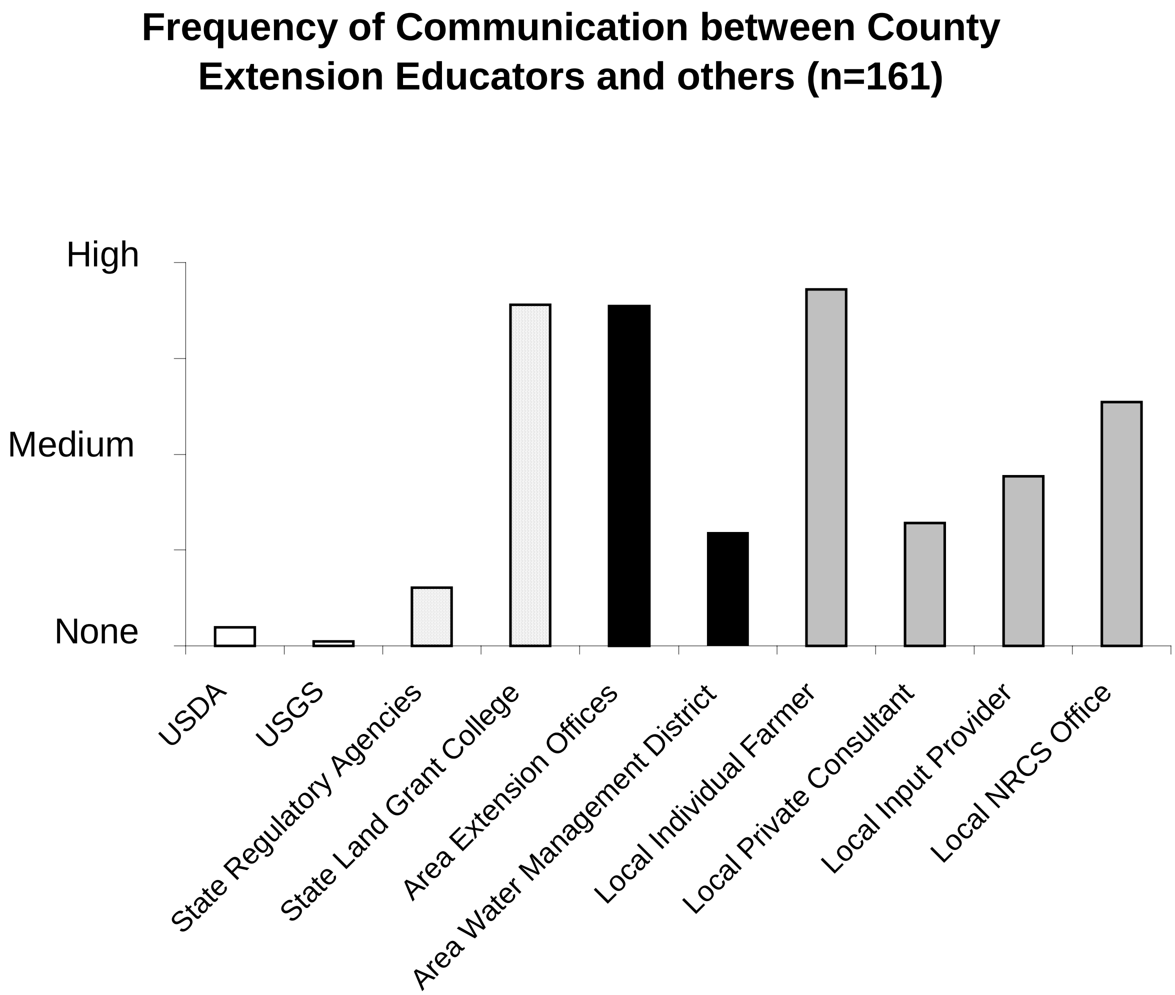
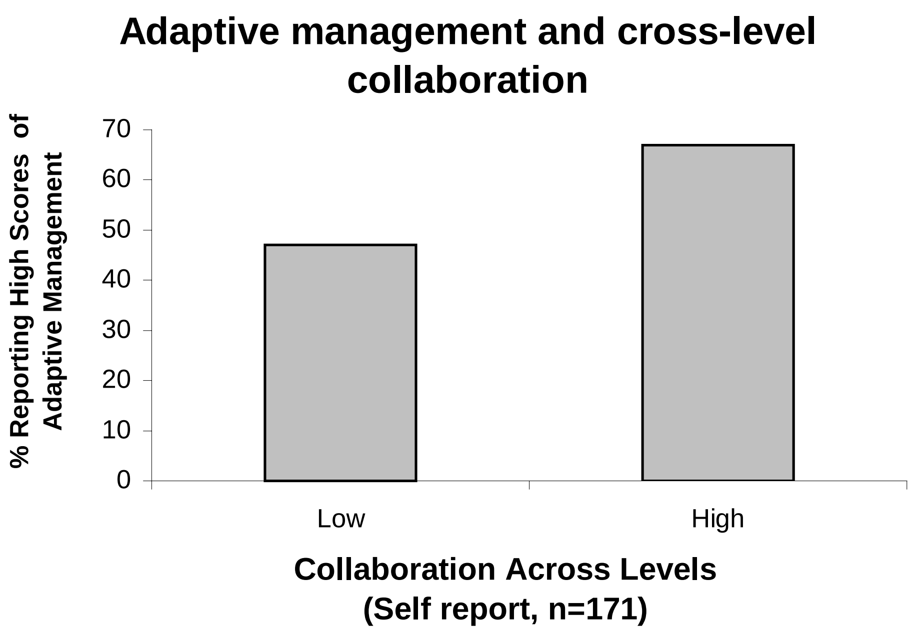


FIGURE 6: This graphs suggests an association between the amount of collaboration which crosses multiple levels and adaptive management.



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